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Abstract. Sete Cidades is an active central volcano with a summit caldera located in the westernmost part of S. Miguel Island (Azores). Since the settlement of the Island, in the 15th century, many landslide events occurred in this volcano, causing extensive damages in buildings and infrastructures. The study of historical records and the observation of new occurrences showed that landslides in the region have been triggered by heavy rainfall periods, earthquakes and erosion.

In order to assess landslide susceptibility at Sete Cidades Volcano, landslide scars and associated deposits were mapped through aerial photographs and field surveys. The obtained data were inserted in a GIS to produce a landslide distribution map. It was concluded that the high density landslide areas are related with (1) major scarp faults, (2) the margin of fluvial channels, (3) the sea cliffs and (4) volcanic landforms, namely the caldera wall. About 73% of the mapped events took place in areas where pyroclastic deposits are the dominant lithology and more than 77% occurred where slopes are equal or higher than 20°. These two parameters were integrated and used to generate a preliminary susceptibility map.

The incorporation of vulnerability data into the GIS allowed concluding that 30% of dwellings and most of the roads on Sete Cidades Volcano are located in areas where landslide susceptibility is high to very high. Such conclusion should be taken into account for emergency and land use planning.

1 Introduction

The Azores archipelago is formed by nine volcanic islands and is located in the Atlantic Ocean, between 37°–40° N latitude and 25°–31° W longitude (Fig. 1).

The geological setting of the Azores region is dominated by the existence of a mantle plume where the American, Eurasian and African plates meet (White et al., 1979; Searle, 1980). The Mid-Atlantic Ridge and the Terceira Rift are the most important tectonic structures recognised in the area (Fig. 2), being the main source of the seismic and volcanic activity registered in the region (Machado, 1959; Weston, 1964). Since the settlement of the archipelago, in the 15th century, many destructive earthquakes, volcanic eruptions and landslides were responsible for several deaths and substantial damage.

São Miguel, with about half of the Azores inhabitants, is the largest island of the archipelago and is located in the eastern part of the Terceira Rift. The island is formed by several volcanic edifices placed along a general E-W direction and is crossed by NW-SE, NE-SW, WNW-ESE and E-W regional tectonic structures (Fig. 3). Sete Cidades Volcano is located in the westernmost part of S. Miguel occupying an area of about 110 km^2. It is an active central volcano with a summit caldera and its eruptive history was marked by two distinct periods: the first one was dominated by the extrusion of lava flows forming the basal part of the volcanic edifice; the second, starting 36 000 years ago, was characterised by the emplacement of major pyroclastic flows and tephra fall deposits.

2 Historical accounts and recent events

Since the settlement of the island many catastrophic landslides occurred at S. Miguel Island. The largest event was triggered by the 1522 AD earthquake and destroyed the former capital of the Azores, Vila Franca do Campo, located in the south flank of Fogo Volcano, killing about 5000 people (Marques et al., 2004)[1].

At Sete Cidades Volcano, the history reveals that landslides have also been the cause of extensive damages in buildings and infrastructures. The study of historical records and

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[1]Marques, R., Gaspar, J. L. and Zêzere, J. L.: Reconstruction of the 1522 earthquake-induced landslide of Vila Franca do Campo (São Miguel Island, Azores), Eng. Geology, in revision, 2004.

Table 1. Lithological classes and landslide density per km^2.

Lithological class	Outcropping area (km^2)	Outcrop area %	Number of landslides	% of landslide (over the total)	Landslide density per km^2
L1	21,90	16,63	41	4,6	1,87
L2	35,74	27,13	197	22,2	5,51
L3	74,07	56,24	648	73,1	8,74

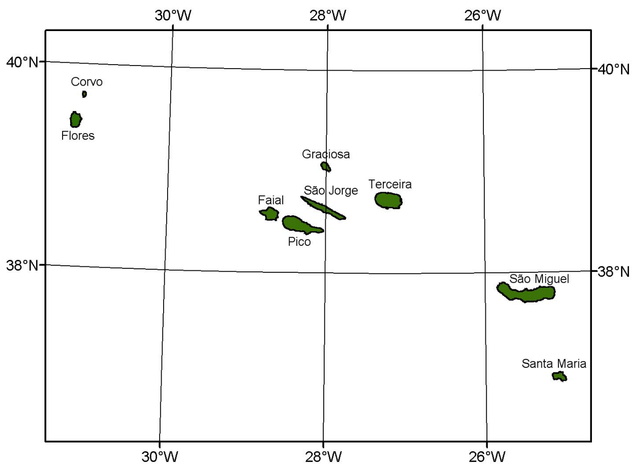

Fig. 1. Geographical location of the Azores archipelago.

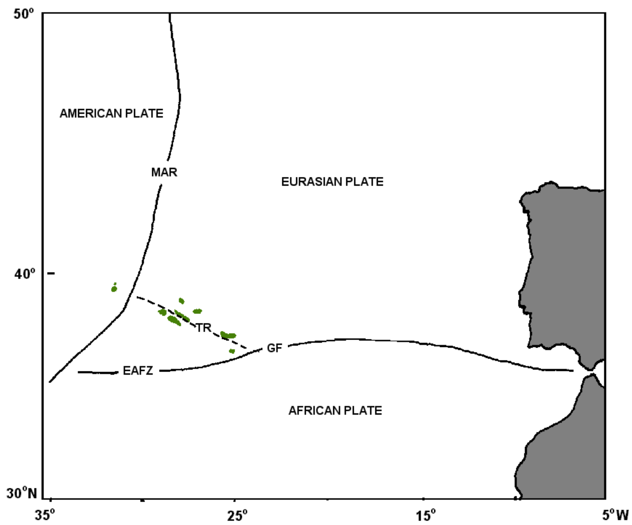

Fig. 2. Main tectonic structures in the Azores region. MAR – Mid-Atlantic Ridge; EAFZ – East Azores Fracture Zone; TR – Terceira Rift; GF – Gloria Fault (in: Gaspar et al., 1999).

the observation of new occurrences showed that heavy rainfall, earthquakes and erosion have triggered landslides in the region. On 8 December 1713, several landslides took place in the W flank of the volcano and important debris flows developed along some streamlines. Those events occurred associated to an intense seismic crisis that began on 14 November and lasted for about three weeks (e.g. Queiroz, 1997; Sil-

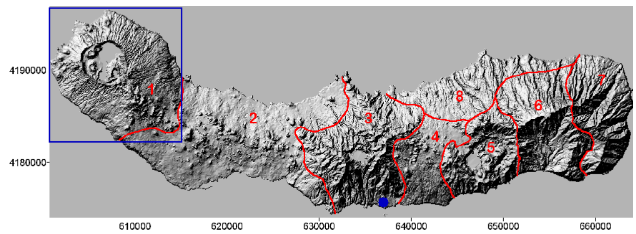

Fig. 3. Main morphological provinces of S. Miguel Island (Zbyszewski, 1961). 1 – Sete Cidades Volcano; 2 – Picos Volcanic System; 3 – Fogo Volcano; 4 – Achada das Furnas Volcanic System; 5 – Furnas Volcano; 6 – Povoação Volcano; 7 – Nordeste Volcanic Complex; 8 – North Platform (in: Wallenstein, 1999). ☐ – Study area; blue ● – Vila Franca do Campo, the former capital of Azores.

veira, 2002). No casualties were reported at the time. On 21 November 1988, landslides occurred following a 5.8 magnitude earthquake with epicentre 20 km west of the island. Most of the events were of debris flows type and cut the main roads around the volcano.

More recently, in January and February 2002, several landslides triggered by heavy rainfall associated with strong wind occurred in the SW flank of the volcano. At that time many dwellings were affected and roads cut (Malheiro and Dias, 2002) (Figs. 4 and 5). In February 2003, many landslides were observed in the NE sector of the volcano also triggered by an intense rainfall phenomenon (Fig. 6) and in October of the same year a road was cut in the W coast when a landslide occurred in the cliff as result of the normal coastal erosion process (Marques and Amaral, 2003) (Fig. 7).

In general, important landslides happen in Sete Cidades Volcano at least once a year, causing damages in dwellings, roads and other basic infrastructures.

Taking into account the idea that many landslides take place in zones already affected in the past (Carrara et al., 1995; Parise and Wasowski, 1999; Zêzere, 2001) and the principle that geological and geomorphological conditions verified in past landslides can be identical in futures events (Carrara et al., 1998), it is crucial to recognise the distribution of past landslides and to analyse the local factors that may have contributed to their occurrence. With the purpose to assess landslide susceptibility at Sete Cidades Volcano, three main parameters were considered at this stage: (1) the landslide distribution, (2) the lithology and (3) the slope steepness.

Fig. 4. Landslide scar generated during the January 2002 episode (Photo from CVARG).

Fig. 5. January 2002 landslide deposit affecting the wall of a house (Photo from LREC).

3 Landslide mapping

Landslide scars, and when possible the associated deposits, were mapped using aerial photographs (1:8000 and 1:15 000) from different years (1974, 1977, 1982, 1995 and 1998) and several field surveys were conducted to characterise the most recent events. A total of 886 landslides were recognised, corresponding to more than 31% of the total events mapped in S. Miguel Island (Valadão et al., 2002).

The obtained data were introduced in a Geographic Information System (GIS) to produce the landslide distribution map presented in Fig. 8. The higher density landslide areas reveal a close relationship with the observed geological and geomorphological structures including (1) major scarp faults, (2) the margin of fluvial channels, (3) the sea cliffs and (4) volcanic landforms, namely the caldera wall and some cinder cones.

Specific evaluations of landslide susceptibility have shown specific differences between seismic and rainfall triggering events (Brabb, 1995). Unfortunately, except for the 2002 and 2003 recent events it was not possible to establish any relation between landslides and their trigger mechanisms.

4 Lithological classes

Three main classes of lithology were established for this study based in the S. Miguel Island Geological Map (Moore, 1991) and considering the vulcanostratigraphy of Sete Cidades Volcano (Queiroz, 1997): (1) class L1, essentially composed by lava flows; (2) class L2, characterized by both pyroclastic deposits and lava flows; and (3) class L3, where pyroclastic deposits are the dominant volcanic products.

The spatial distribution of such classes in the volcano region (Fig. 9) allowed to conclude that 56% of the area is generally covered by pyroclastic deposits while only 16,6% is composed by superimposed lava flows (Table 1). The analysis of the landslide distribution taking into account the lithology indicates that 73% of the events occurred in zones where pyroclasts are dominant and just 4,6% took place in areas covered by lava flows. This difference persists when it is considered the landslide density per square kilometre (Table 1) and is due to the fact that the majority of the young pyroclastic products that cover the all area are of fall origin and form unconsolidated deposits that are more straightforwardly removed. This observation also explains why debris flows are the most common type of landslides that occur in Sete Cidades Volcano while rock fall events are restricted to the sea cliffs where lava flows are the dominant lithology.

5 Slope steepness

In order to study the relation between landslide distribution and slope steepness a digital elevation model was created

Fig. 6. Landslide scar and associated deposit formed in February 2003 (Photo from CVARG).

Fig. 7. Road cut in the NW coast of Sete Cidades Volcano as result of the October 2003 event (Photo from CVARG).

Table 2. Number and percentage of landslides vs. slope steepness classes.

Slope steepness class (°)	Number of landslide	% of landslide
0–5	27	3,0
5–15	99	11,2
15–20	73	8,4
20–30	210	23,7
≥30	477	53,8
Total	886	100

Table 3. Weight given to the lithology classes.

Lithology classes	Landslide susceptibility	Weight
L1	Very-low to low	1
L2	Moderate	2
L3	High to very-high	3

Table 4. Weight given to the slope steepness classes.

Slope steepness class	Landslide susceptibility	Weight
0°–15°	Very-low to low	1
15°–20°	Moderate	2
≥20°	High to very-high	3

Table 5. Number and percentage of dwellings in areas with different landslide susceptibility.

Susceptibility	Number of dwellings	% of dwellings
Very-low to low	261	6
Moderate	2784	64
High to very-high	1305	30

with the GIS ArcView® 3.3 software using the elevation contour lines from the 2001 digital S. Miguel Military Map (Sheets 26, 27 and 31 in 1:25 000) published by the Instituto Geográfico do Exército. The automatic procedure provided by the GIS to produce the slopes map was first applied considering cells with 10 m width and class divisions every 5°.

The number of landslides falling in each class is presented in Fig. 10, showing a normal distribution with a maximum value in the slope class of 30°–35°. Analysing the histogram

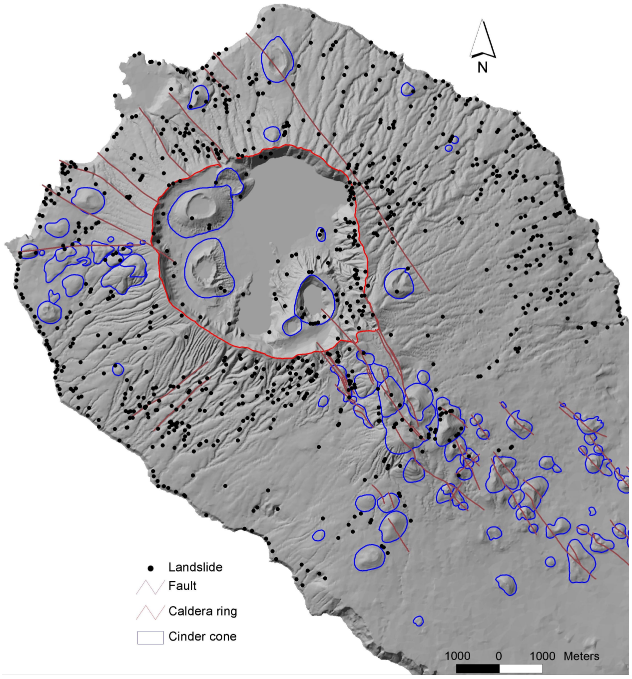

Fig. 8. Sete Cidades main volcano-tectonic structures (Queiroz, 1997) and landslide distribution.

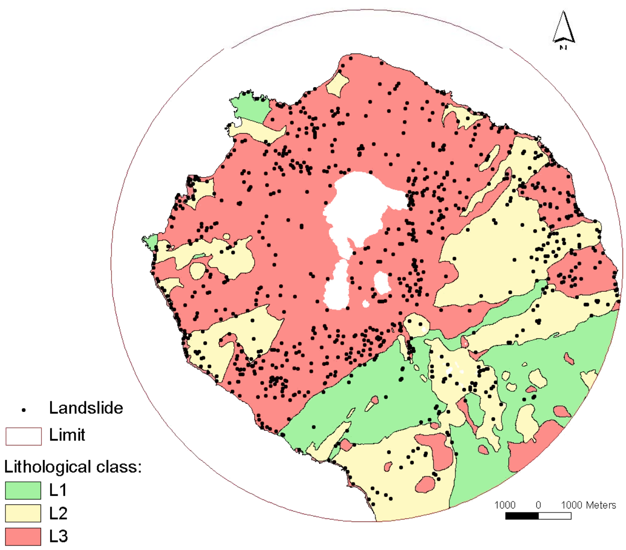

Fig. 9. Lithological map and landslide distribution. Legend: L1 – Mainly lava flows; L2 – Lava flows covered and/or intercalated with pyroclastic deposits; L3 – Mainly pyroclastic deposits.

of Fig. 10 it emerged that five slope steepness intervals could be used to represent the data as it is proposed in Table 2 (e.g. Ruiz and Gijón, 1994; Zêzere, 2001). Based on such simplification a new slope steepness map was produced (Fig. 11). It was concluded that around 54% of the landslides occurred in slopes with steepness equal or higher than 30° and more than 77% were located in zones where the inclination is equal or higher than 20°.

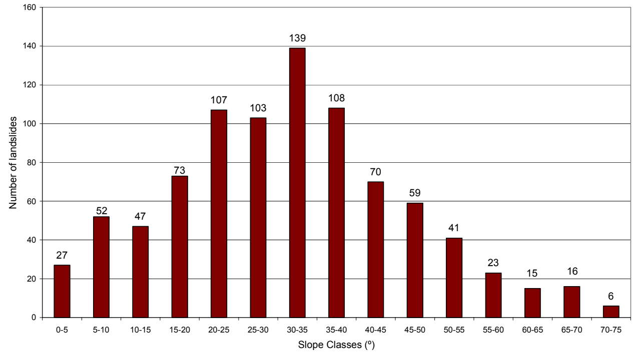

Fig. 10. Number of landslides in each considered slope steepness class.

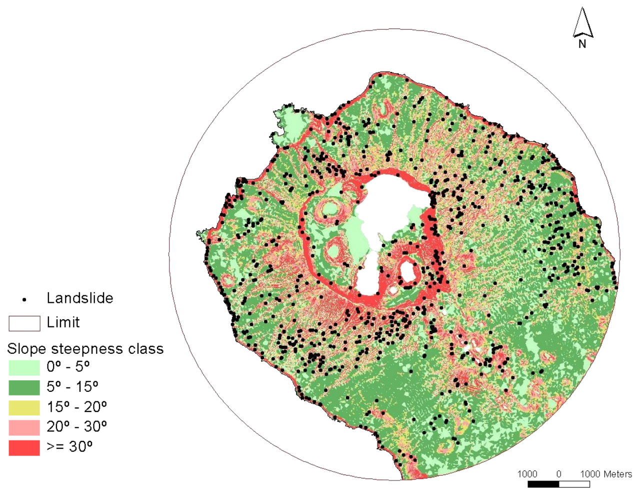

Fig. 11. Slope steepness map and landslide distribution.

6 Discussion and conclusions

The analysis of historical reports and the observation of recent landslide events that took place on Sete Cidades Volcano show that given a certain earthquake or rainfall episode, zones with different lithology or slope steepness behave differently. Debris flows are the most common type of landslides due to the fact that unconsolidated pyroclastic deposits formed during highly explosive volcanic eruptions covers all the area. Rock fall occur with major frequency in the sea cliffs where fractured lava flows from the volcano basement make the dominant lithology.

Based on this statement and taking into account the landslide distribution in the study area, relative weights were attributed to the considered classes of lithology (Table 3) and slope steepness (Table 4). The integration of such data in the GIS allowed to generate the susceptibility map presented in Fig. 12 and revealed that using such parameters landslide susceptibility is high to very-high in about 33% of the area, moderate in 53% and low to very-low in 14%.

Sete Cidades Volcano is part of Ponta Delgada council and comprises ten parishes. According to the Census 2001,

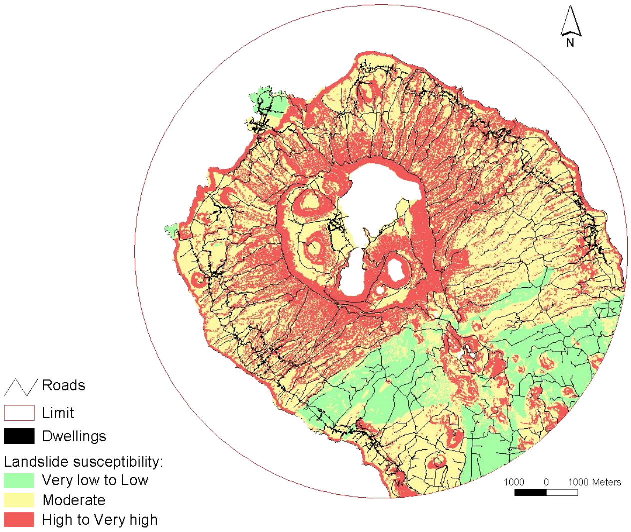

Fig. 12. Landslide susceptibility map and buildings distribution.

11 429 peoples lives around the volcano. A detailed field survey allowed identifying 7019 buildings in the area, 4351 of which are dwellings (Gomes, 2003). The incorporation of the inhabited areas in the GIS (Fig. 12) show that 22% (957) of the houses are placed in zones with high to very-high susceptibility and only 7% (304) in areas of low to very-low susceptibility. The majority of the residences, 71% (3090) are located in areas of moderate susceptibility.

Bearing in mind that the rupture surface of a landslide develops behind the slope face it is clear that even flat terrains can be involved in such occurrences if adjacent to inclined planes. Field observations following the 1997 Ribeira Quente rainfall catastrophic event (Gaspar et al., 1997) and the 1998 Faial earthquake (Senos et al., 1998) allowed to verify that landslide rupture surfaces in zones with similar geology than the one observed at Sete Cidades Volcano occur frequently 5 to 10 m to the interior of the mobilized slopes. Assuming a buffer of 10 m behind the zones with higher steepness, namely the margin of valleys, the sea cliff, scarp faults and the caldera rim, it comes out that the number of dwellings in high to very-high landslide susceptibility zones increase to 30% (Table 5).

The simple methodology that was developed in this study for Sete Cidades Volcano emphasized that landslide risk analysis need to be taken into account concerning land use and emergency planning. Future efforts should consider the vulnerability of houses, basic infrastructures and economic factors.

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